Technische Universiteit **Eindhoven** University of Technology

Student name:

Student number:

Examination cover sheet

(to be completed by the examiner)

Course name: Components in wireless technologies Course code: 5XTC0

Date: 30th of June 2020

Start time: 18:00 End time: 21:00

Number of pages: 9

Number of questions: 4

Maximum number of points/distribution of points over questions: maximum of 40 points (point distribution: see questions)

Method of determining final grade: number of points divided by 4, maximum grade is 10

Answering style: formulation, order, foundation of arguments, multiple choice: See exam questions

Exam inspection:

Other remarks: 1) A list of equations is provided at the end of the exam.

2) This exam determines 50% of your final grade. The minimum grade for this exam must be 5.0.

Instructions for students and invigilators

Permitted examination aids (to be supplied by students):

x Notebook

x Calculator

□ Graphic calculator

x Lecture notes/book

□ One A4 sheet of annotations

□ Dictionar(y)(ies). If yes, please specify:

See also next page for additional details

Important:

- examinees are only permitted to visit the toilets under supervision
- it is not permitted to leave the examination room within 15 minutes of the start and within the final 15 minutes of the examination, unless stated otherwise
- examination scripts (fully completed examination paper, stating name, student number, etc.) must always be handed in
- the house rules must be observed during the examination
- the instructions of examiners and invigilators must be followed
- no pencil cases are permitted on desks
- examinees are not permitted to share examination aids or lend them to each other

During written examinations, the following actions will in any case be deemed to constitute fraud or attempted fraud:

- using another person's proof of identity/campus card (student identity card)
- having a mobile telephone or any other type of media-carrying device on your desk or in your clothes
- using, or attempting to use, unauthorized resources and aids, such as the internet, a mobile telephone, etc.
- using a clicker that does not belong to you
- having any paper at hand other than that provided by TU/e, unless stated otherwise
- visiting the toilet (or going outside) without permission or supervision

Exam Components in wireless technologies (5XTC0), re-sit 30/06/2020.

- This exam consists of four problems.
- In total you can achieve 40 points. The grade of this exam is #points/4, i.e. maximum is 10.
- This exam determines 50% of your final grade. The minimum grade of this exam must be 5.0.

For question 3 and question 4 you can make use of the list of equations given at the end of the exam.

RULES:

Answering and Submitting Questions:

- You need to answer the questions on your own paper.
- For the Smith chart questions, you may use pre-printed hardcopies of Smith charts (no printing allowed during the exam). Alternatively, you may use the PowerPoint tool that is provided in CANVAS.
- Once you are finished or the time is nearly up, you need to upload your answer sheets on Canvas (scan, photo or similar). The following file types are allowed for the upload: jpg, ppt, pptx, pdf, png. Note that zip-files will be rejected by the system. You can upload multiple files instead. Note that your worked-out solutions must be readable to us, otherwise you will not get any points.
- If you are finished before the exam time is up, you need to inform us before you take pictures. We will then take a note and allow you to use your phone for taking pictures.
- You must put your student card on every photo.
- Canvas will not allow uploads of your answer after the exam time has ended. Make sure you upload in time (late arrivals by email will not be marked).

Other rules:

- In case of questions or if you need to go to the toilet, you can use the “raise hand” function in MS Teams. We will then set up an individual sub-call with you.
- Phone use during the exam is not allowed. If you want to take pictures, first use the “raise hand” function (above).
- You are allowed to use a non-programmable calculator as well as a compass and ruler.
- This is an open book exam, i.e. you are allowed to use the slides, books and own notes.
- You have to work on your own, i.e. teamwork and copying answers from others is strictly prohibited! In case of suspected plagiarism, individual oral exams with the respective student(s) will be scheduled after the written exam to verify the validity of the outcome of the exam.

GOOD LUCK!!!

Question 1: Transmission lines and microwave networks (10 points)

A load impedance $Z_L = (15 + j39)\Omega$ is connected to a transmission line network as shown in Figure 1. The network consists of two transmission lines, one with characteristic impedance $Z_0 = 75\Omega$ and length $l_0 = 0.5$m and the other one with characteristic impedance $Z_1 = 150\Omega$ and length $l_1 = 0.321m$. In between the two transmission lines there is a matching network consisting of impedances Z_p and Z_s. The whole setup is driven by a generator with internal impedance $Z_0 = 75\Omega$ at an operating-frequency of 400 MHz.

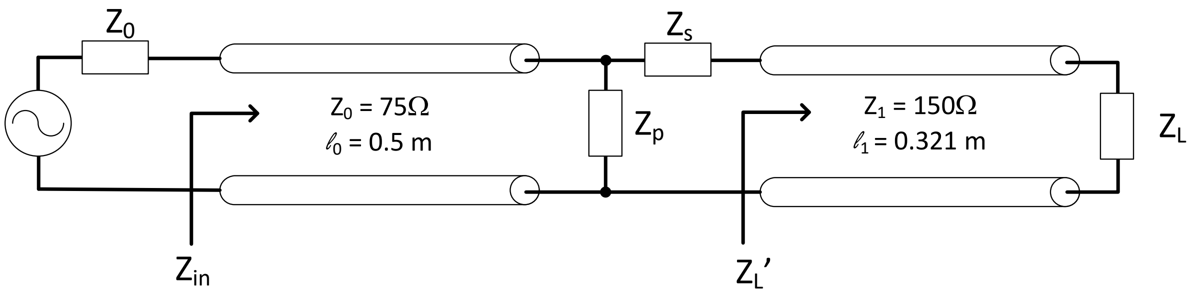


Figure 1: Setup for Question 1a)-d).

a) Determine the magnitude and phase of the reflection coefficient of Z_L with respect to the characteristic impedance $Z_1 = 150\Omega$.

b) Use the Smith Chart to determine the equivalent impedance Z_L' at the beginning of the transmission line with characteristic impedance Z_1. Make clear how you get to your answer (clear markings in the Smith Chart or a written explanation).

c) Use your solution from b) and the Smith chart to determine the values for Z_p and Z_s of the matching network, such that the maximum power is delivered from the generator to the load impedance Z_L. Make clear how you get to your answer (clear markings in the Smith Chart or a written explanation).

Consider now the setup shown in Figure 2.

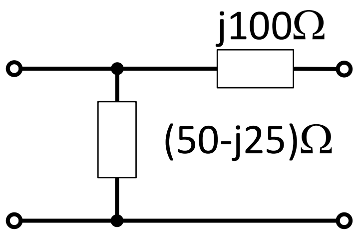


Figure 2: Setup for e)-f).

d) Determine the S-matrix, [S], of the setup shown in Figure 2.

e) Is the scattering matrix of the setup shown in Figure 2 unitary ($[S]^t[S]^* = [U]$)? Explain your answer.

Question 2: Antenna system analysis (10 points)

Consider the setup shown in Figure 3 and the table provided below. Both transmitter and receiver use identical antennas with directivity and radiation efficiency as provided in the table. Unless indicated otherwise, all devices are perfectly matched to each other, antennas are linearly polarized, antennas are oriented such that their polarizations align, and you may assume a direct line-of-sight between the antennas.

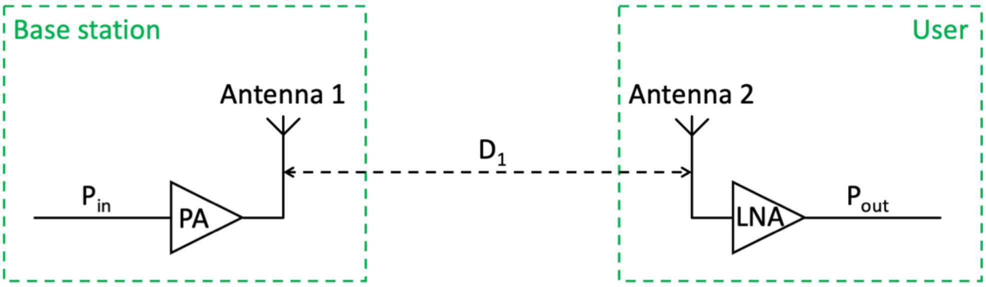


Figure 3: Setup for Question 2a)-2c).

Centre frequency f_c	3 GHz
Power gain of the base station's power amplifier (PA), G_{PA}	15 dB
Power gain of the user's low-noise amplifier (LNA), G_{LNA}	18 dB
Antenna 1 gain (base station), $G_{ant,1}$	21 dBi
Antenna 2 gain (user), $G_{ant,2}$	0 dBi
Distance base station to user, D_1	2 km

a) Calculate the Equivalent Isotropically Radiated Power (EIRP) of the base station when P_{in} = 10 dBm at the base station's PA input.
b) It is now desired to obtain P_{out} = -65 dBm at the output of the user's LNA. Calculate the required P_{in} at the base-station to achieve this. Provide your answer both in [dBm] and in [mW].
c) Suppose antenna 2 has a total efficiency of 10%. What is its directivity $D_{ant,2}$ in dBi?

Unfortunately for the user, a source of interference has popped up at the same frequency, as shown in Figure 4, with the properties given in the table below.

Interferer output power P_{int}	12 dBm
Antenna 3 gain (interferer), $G_{ant,3}$	5 dBi
Distance interferer to user, D_2	1 km

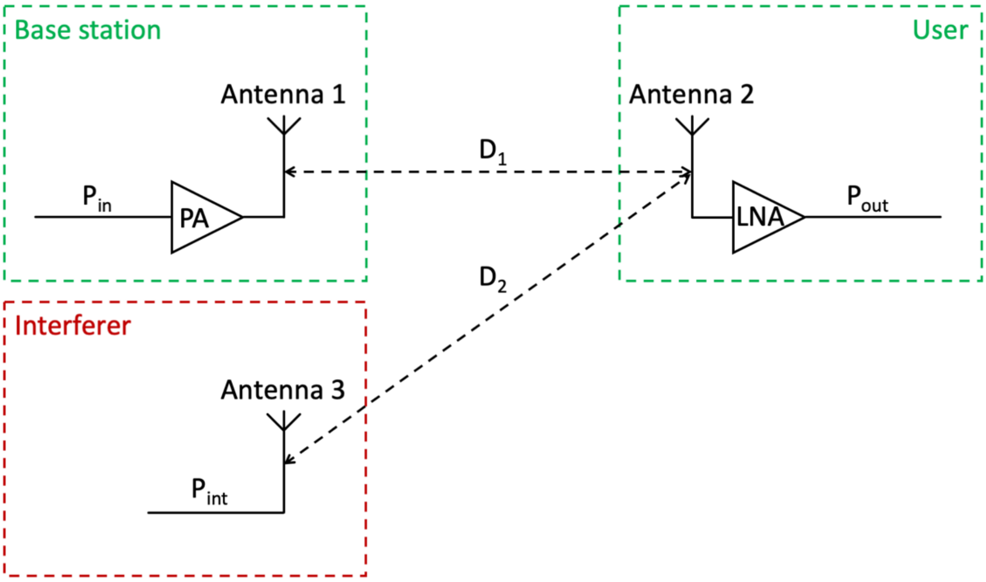


Figure 4: Setup for Question 2d)-e).

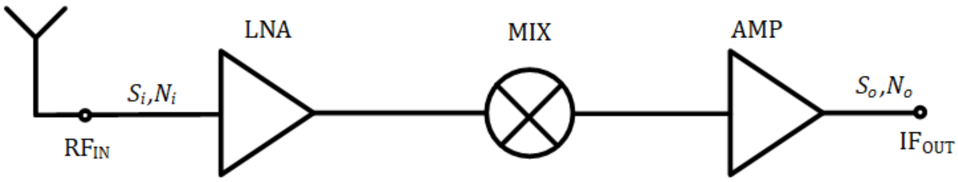
d) The interferer is located at the edge of the half-power beam width (HPBW) of the user. What is the minimum power due to the interfering signal (only!) at the output of the user's LNA?

e) The user, who is in an environment with a lot of buildings, notices large differences in the power received from both the base station and the interferer when the antenna is moved only slightly. What would be the probable cause for this?

Question 3: Wireless receiver (8 points)

Note: At the end of the exam a list of equations is given.

The block diagram of the wireless receiver is shown in figure below. The data describing the wireless receiver are provided in the text following the figure. The wireless receiver consists of Low Noise Amplifier (LNA), Mixer (MIX) and Amplifier (AMP). *Si* and N_i denote signal and noise at the RF input (RF_{IN}). S_o and N_o denote signal and noise at the IF output (IF_{OUT}).



LNA gain: $G_{LNA}[dB] = 15dB$

LNA noise figure: $NF_{LNA} = 2dB$

MIX gain: $G_{MIX}[dB] = 10dB$

MIX noise figure: $NF_{MIX} = 10dB$

AMP gain: $G_{AMP}[dB] = 20dB$

AMP noise figure: $NF_{AMP} = 5dB$

System temperature: $\mathrm{T}_0 = 290K$

IF bandwidth: $B = 10MHz$

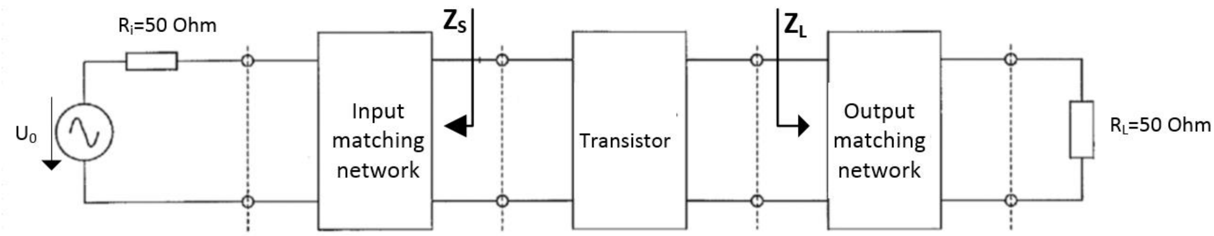
Boltzmann constant: $k_B = 1.38 \cdot 10^{-23} \dfrac{Watt \cdot s}{K}$

a) Calculate the overall noise figure (*NF*) of the wireless receiver.
b) Which block in wireless receiver has the largest impact on the overall noise figure? Explain your answer.
c) If the input noise power from a feeding antenna is $Ni = k_B T_0 B$, find the output noise power and express it in dBm.
d) If a minimum signal-to-noise ratio (SNR) of 20dB is required at the IF output (IF_{OUT}), what is the minimum signal (so called receiver sensitivity) that should be applied at the RF input (RF_{IN}). Express the receiver sensitivity in dBm.

Question 4: Amplifier design (12 points)

<u>Note: At the end of the exam a list of equations is given.</u>

The block diagram of the amplifier is shown in the figure below. It consist of a transistor and matching networks at the input and at the output.



The S-parameters of the transistor are given below for a reference impedance of Z_0=50 Ω at a frequency f_0 = 5 GHz.

$$S_{11}=0.8, \sphericalangle -150^\circ$$
$$S_{12} = 0$$
$$S_{21}=3.93, \sphericalangle 60^\circ$$
$$S_{22}=0.6, \sphericalangle -70^\circ$$

In addition, the transistor has the following noise parameters:

$$NF_{min} = 1.5 \text{ dB}$$

$$\Gamma_{opt} = 0.7 \sphericalangle 100^\circ$$

$$r_n = 3\ \Omega$$

a) Determine whether this amplifier is unconditionally stable.
b) How must the source reflection coefficient Γ_S and load reflection coefficient Γ_L be chosen to achieve maximum trasnducer power gain $G_{TU,max}$.
c) Determine $G_{TU,max}$. Express your answer in dB.
d) Design a 2-element matching network at the input of the amplifier to reach conjugate matching to a 50 Ω source impedance. Illustrate your answer in the Smith chart.
e) Calculate the constant gain circle for G_S=2 dB and indicate it in the Smith chart.
f) Calculate the center and the radius of the 3 dB constant noise figure circle. Draw the 3 dB constant noise figure circle in the Smith chart.

List of Equations (only some of these equations are required to solve questions 3 and 4)

Power delivered to the load	$P_L = \frac{\lvert V_2^-\rvert^2}{2Z_0}\left(1-\lvert\Gamma_L\rvert^2\right)$
Input power to the network	$P_{in} = \frac{\lvert V_1^+\rvert^2}{2Z_0}\left(1-\lvert\Gamma_{in}\rvert^2\right)$
Input and output reflection coefficients of a transistor with a source and load: general case	$\Gamma_{in} = \frac{V_1^-}{V_1^+} = S_{11} + \frac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}$ $\Gamma_{out} = \frac{V_2^-}{V_2^+} = S_{22} + \frac{S_{12}S_{21}\Gamma_S}{1-S_{11}\Gamma_S}$
Input and output reflection coefficients of a transistor with a source and load: unilateral case	$\Gamma_{in} = \frac{V_1^-}{V_1^+} = S_{11}$ $\Gamma_{out} = \frac{V_2^-}{V_2^+} = S_{22}$
Gain of the input matching network	$G_S = \frac{1-\lvert\Gamma_S\rvert^2}{\lvert 1-\Gamma_{\text{in}}\Gamma_S\rvert^2}$
Gain of the output matching network	$G_L = \frac{1-\lvert\Gamma_L\rvert^2}{\lvert 1-S_{22}\Gamma_L\rvert^2}$
Gain of the transistor (unilateral case)	$G_0 = \lvert S_{21}\rvert^2$
Transducer gain of the basic amplifier circuit (input matching, unilateral transistor, output matching)	$G_T = G_S G_0 G_L$ $G_{T,dB} = G_{S,dB} + G_{0,dB} + G_{L,dB}$
Maximum gain of the input and output matching networks	$G_{S\max} = \frac{1}{1-\lvert S_{11}\rvert^2},$ $G_{L\max} = \frac{1}{1-\lvert S_{22}\rvert^2}.$
Maximum transducer power gain, unilateral case	$G_{TU\max} = \frac{1}{1-\lvert S_{11}\rvert^2}\lvert S_{21}\rvert^2\frac{1}{1-\lvert S_{22}\rvert^2}$
Normalized gain factors g_s and g_L	$g_S = \frac{G_S}{G_{S\max}} = \frac{1-\lvert\Gamma_S\rvert^2}{\lvert 1-S_{11}\Gamma_S\rvert^2}(1-\lvert S_{11}\rvert^2),$ $g_L = \frac{G_L}{G_{L\max}} = \frac{1-\lvert\Gamma_L\rvert^2}{\lvert 1-S_{22}\Gamma_L\rvert^2}(1-\lvert S_{22}\rvert^2).$
Center and radius of the constant gain circle for the input matching network	$C_S = \frac{g_S S_{11}^*}{1-(1-g_S)\lvert S_{11}\rvert^2},$ $R_S = \frac{\sqrt{1-g_S}\,(1-\lvert S_{11}\rvert^2)}{1-(1-g_S)\lvert S_{11}\rvert^2}$
Center and radius of the constant gain circle for the output matching network	$C_L = \frac{g_L S_{22}^*}{1-(1-g_L)\lvert S_{22}\rvert^2},$ $R_L = \frac{\sqrt{1-g_L}\,(1-\lvert S_{22}\rvert^2)}{1-(1-g_L)\lvert S_{22}\rvert^2}$

Condition for "unconditionally stable" device, general case	for all $\lvert\Gamma_L\rvert<1$ and $\lvert\Gamma_S\rvert<1$ $\Rightarrow \begin{cases} \lvert\Gamma_{in}\rvert = \left\lvert S_{11}+\dfrac{S_{12}S_{21}\Gamma_L}{1-S_{22}\Gamma_L}\right\rvert<1 \\ \lvert\Gamma_{out}\rvert = \left\lvert S_{22}+\dfrac{S_{12}S_{21}\Gamma_S}{1-S_{11}\Gamma_S}\right\rvert<1 \end{cases}$
Conditions for "unconditionally stable" device, unilateral case	$\lvert\Gamma_{in}\rvert=\lvert S_{11}\rvert<1$ $\lvert\Gamma_{out}\rvert=\lvert S_{22}\rvert<1$
Center and radius of the stability circles, load side	$C_L=\dfrac{(S_{22}-\Delta S_{11}^*)^*}{\lvert S_{22}\rvert^2-\lvert\Delta\rvert^2}$ (center), $R_L=\left\lvert\dfrac{S_{12}S_{21}}{\lvert S_{22}\rvert^2-\lvert\Delta\rvert^2}\right\rvert$ (radius). $\Delta = S_{11}S_{22}-S_{12}S_{21}$
Center and radius of the stability circles, source side	$C_S=\dfrac{(S_{11}-\Delta S_{22}^*)^*}{\lvert S_{11}\rvert^2-\lvert\Delta\rvert^2}$ (center), $R_S=\left\lvert\dfrac{S_{12}S_{21}}{\lvert S_{11}\rvert^2-\lvert\Delta\rvert^2}\right\rvert$ (radius) $\Delta = S_{11}S_{22}-S_{12}S_{21}$
Test for unconditional stability, general case	$\lvert\Delta\rvert=\lvert S_{11}S_{22}-S_{12}S_{21}\rvert<1$ **and** $K=\dfrac{1-\lvert S_{11}\rvert^2-\lvert S_{22}\rvert^2+\Delta^2}{2\lvert S_{12}S_{21}\rvert}>1$
Test for unconditional stability, unilateral case	$\lvert S_{11}\rvert<1$ $\lvert S_{22}\rvert<1$
Noise figure of a 2-port amplifier	$F=F_{\min}+\dfrac{r_N}{g_S}\left\lvert y_S-y_{opt}\right\rvert^2$ $F=F_{\min}+4r_N\dfrac{\lvert\Gamma_S-\Gamma_{opt}\rvert^2}{\left(1-\lvert\Gamma_S\rvert^2\right)\cdot\lvert 1+\Gamma_{opt}\rvert^2}$
Constant noise circles	$C_F=\dfrac{\Gamma_{opt}}{1+N}$ $R_F=\dfrac{1}{1+N}\sqrt{N^2+N(1-\lvert\Gamma_{opt}\rvert^2)}$ $F_{min}=10^{\frac{NF_{min}}{10}}$ $\Delta F_n'=N=\left(F-F_{\min}\right)\dfrac{\lvert 1+\Gamma_{opt}\rvert^2}{4r_n}=\dfrac{\lvert\Gamma_S-\Gamma_{opt}\rvert^2}{1-\lvert\Gamma_S\rvert^2}$
Output noise, input noise, equivalent noise temperature, noise factor and noise figure	$N_o=Gk_B(T_0+T_e)B$ $N_i=k_BT_0B$ $F=\dfrac{\frac{S_i}{N_i}}{\frac{S_o}{N_o}}=\dfrac{S_i}{S_o}\dfrac{N_o}{N_i}=\dfrac{1}{G}\dfrac{Gk_B(T_0+T_e)B}{k_BT_0B}=1+\dfrac{T_e}{T_0}$ $NF=10\log_{10}F$

Three-stage amplifier: **Output noise ($P_{n,total}$), noise factor (F_{total}) noise figure (NF_{total})**	$P_{n,total} = G_{A3}G_{A2}G_{A1}P_{n,in} + G_{A3}G_{A2}P_{n1} + G_{A3}P_{n2} + P_{n3}$ $F_{total} = \frac{P_{n,total}}{G_{A3}G_{A2}G_{A1}P_{n,in}}$ $F_{total} = 1 + \frac{P_{n1}}{G_{A1}P_{n,in}} + \frac{P_{n2}}{G_{A1}G_{A2}P_{n,in}} + \frac{P_{n3}}{G_{A3}G_{A2}G_{A1}P_{n,in}}$ $F_{total} = F_1 + \frac{F_2-1}{G_{A1}} + \frac{F_3-1}{G_{A1}G_{A2}}$ $NF_{total} = 10\log_{10} F_{total}$ Noise factor of single stage $F_j = 1 + \frac{P_{nj}}{G_{Aj}P_{n,in}}, j = 1,2,3$ Noise figure of single stage $NF_j = 10\log_{10} F_j, j = 1,2,3$
Receiver sensitivity	$P_{sens}\,[dBm] = k_B T_0 B[dBm] + NF_{total}[dB] + SNR[dB]$ $P_{sens}\,[dBm] = -174 + NF_{total} + 10\log_{10} B + SNR$
Conversion Watt to dBm	$P_{sens}\,[dBm] = 10\log_{10}\frac{P_{sens}\,[Watt]}{1mWatt}$ $P_{sens}\,[dBm] = 10\log_{10}\frac{P_{sens}\,[Watt]}{10^{-3}Watt}$
Gain conversion from linear to dB	$G\,[dB] = 10\log_{10} G$